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The Response of Atmospheric and Lower Ionospheric Layer Structures to Gravity Waves

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We solve the linear and quasi-linear problems of the density response of a neutral or ionospheric layer structure of arbitrary density profile to gravity wave perturbations in the background atmosphere. It is shown that the density response of the bottomside of the structure is of larger amplitude than the topside, whereas the general magnitude of the density response depends on the relative sharpness of the layer density gradient in comparison to the gradient of background atmosphere stratification. The sharper the layer gradient, the larger

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the layer density response. Interpretation and application of our results to the ozone and atomic oxygen layers, the sporadic-E layer and to the D and E regions of the ionosphere are discussed.

PREFACE

We are indebted to Dr. K. L. Miller for a discussion of sporadic-E effects, to Dr. B. Wasser and Dr. T. M. Donahue for a preprint of their paper, and to Drs. A. C. Faire and W. D. Komhyr for permission to use their data.

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I. INTRODUCTION

It is well-known that lower ionospheric layers such as the D-layer and the stratospheric ozone layer exhibit large variations of density (see Fig. 1), which are reminiscent of gravity wave structures. Further, in some thin layer structures, such as noctilucent clouds (Fogle and Haurwitz, 1966) and the sporadic-E layer (Miller and Smith, 1975; 1976), the existence of wave-like structure has become a singularly dominant feature. Since the presence of gravity waves of low frequency and short vertical wave-length is expected in the atmosphere, the exhibition of wave structure in atmospheric and lower ionospheric layers is not at all surprising. What is surprising, however, is that the wave-like density variations of the layer structures are generally of large amplitude whereas the density variations in the background atmosphere are usually observed in the middle and upper atmosphere to be less than or of the order of 10-15% (see Fig. 2a, b). For example, the wave-like partial pressure variations of the ozone layer shown in Fig. 1 are of order of 50 μmb out of the layer background partial pressure of some 100 μmb. Density variations associated with such wave-like structures in the middle atmosphere have been observed (Faire et al., 1974). Bounds on the stratospheric wave-like density variations can also be estimated from observed wave-like horizontal wind components in the stratosphere (Webb, 1966) by means of perturbation theory (Hines, 1960). The result is that wave-like density variations in the stratosphere are less than 10% of the background stratospheric density, in agreement with direct density observations. Indeed, one may contrast wave-like density variations of the D and E regions of the ionosphere with that of the neutral atmosphere in the same altitude region and find a similar relationship.

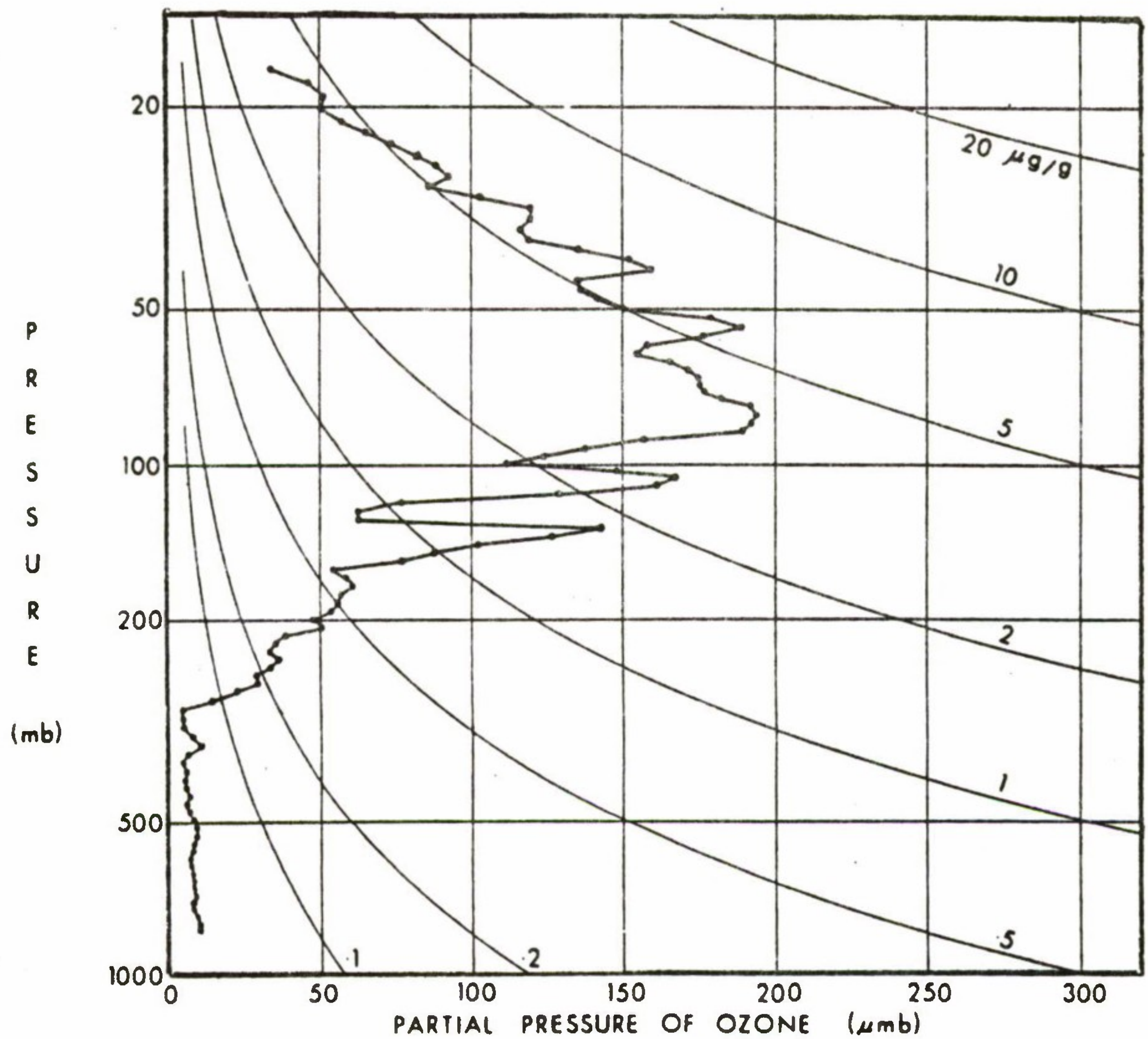

Figure 1. Stratospheric ozone layer showing wave structure. (Komhyr and Gross, 1968).

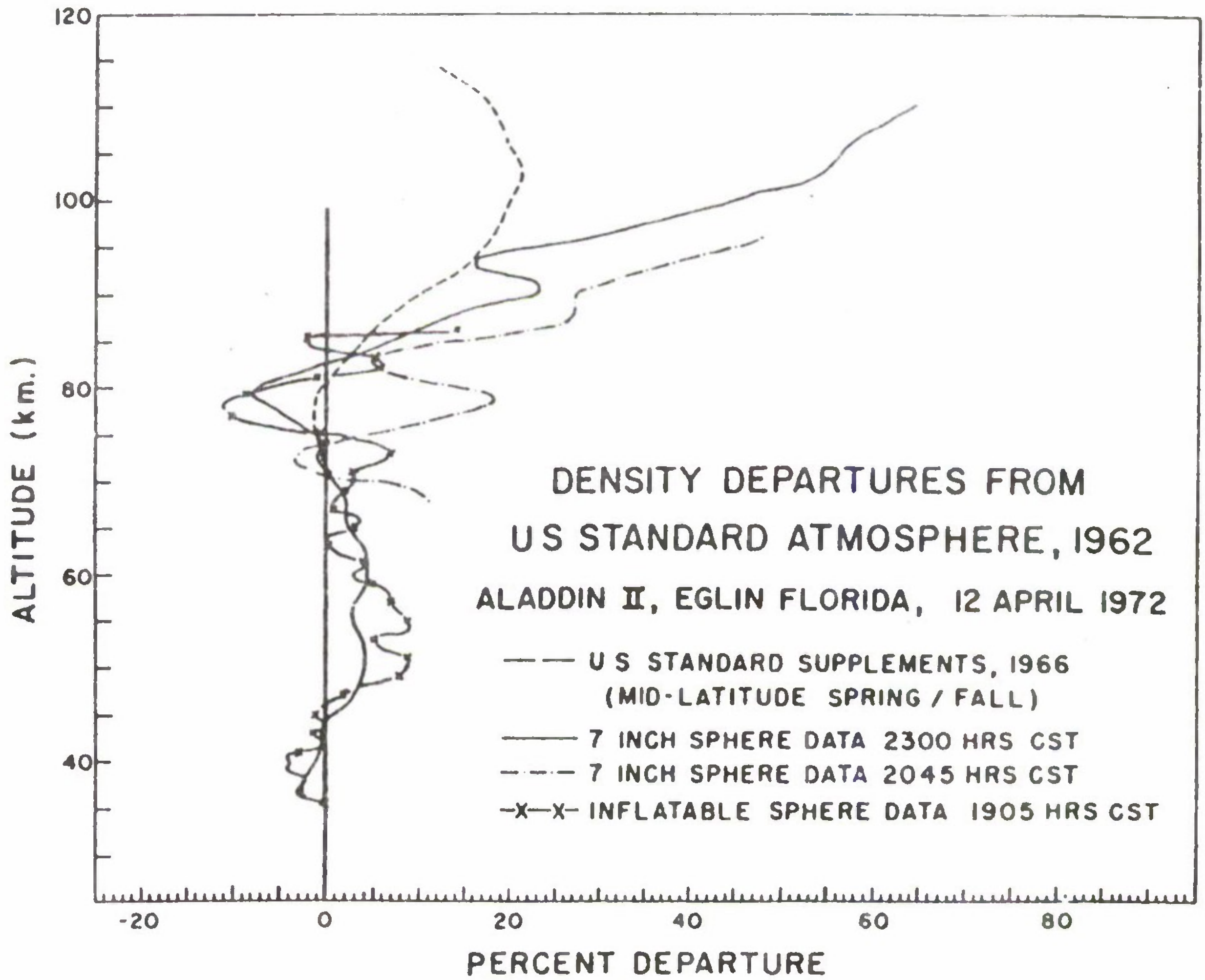

Figure 2a. Wave structure in the stratospheric total density. (Faire et al., 1974).

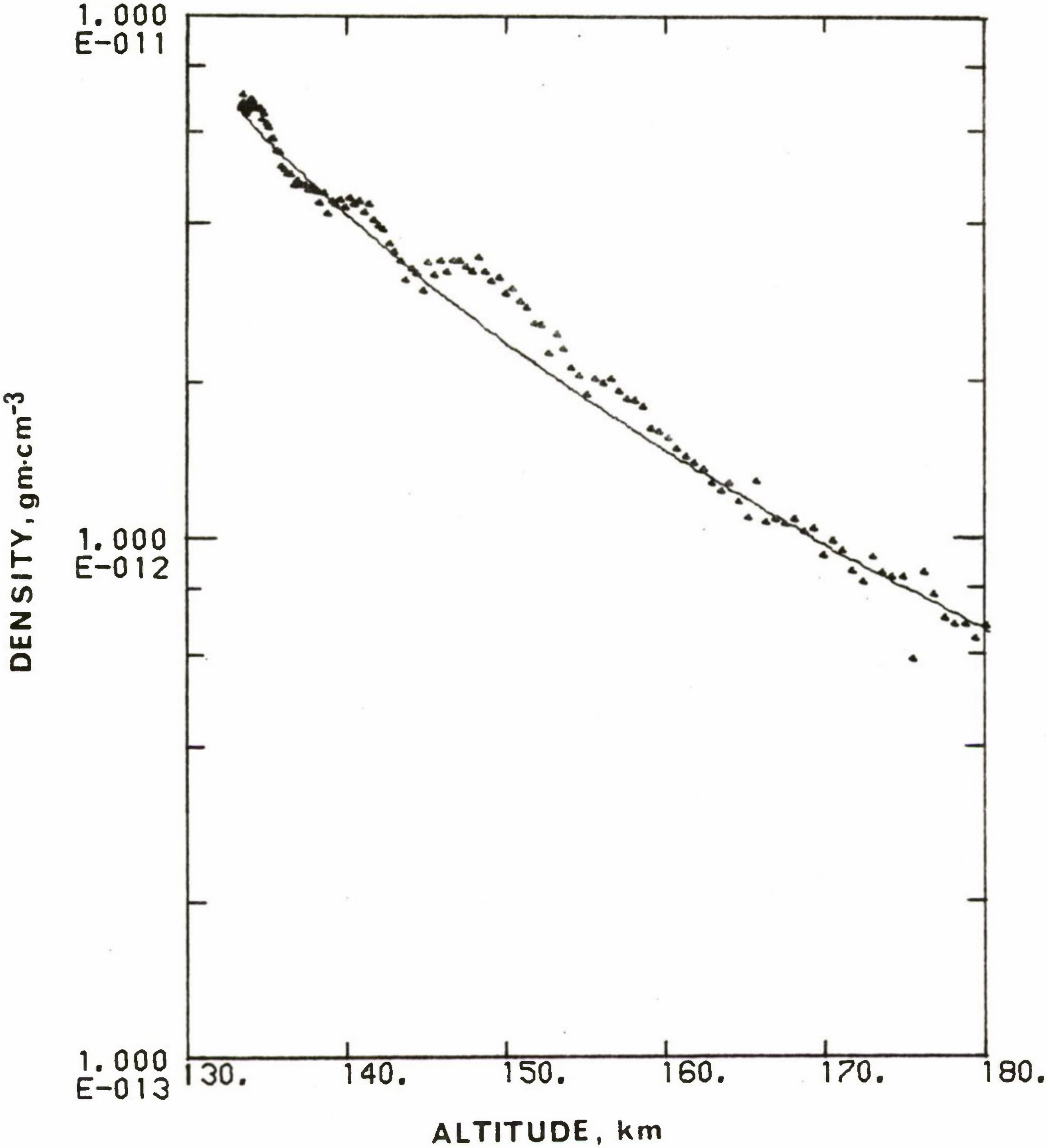

Figure 2b. Wave structure in the lower thermospheric density measured by a satellite-borne accelerometer (Ching, unpublished data).

While numerous authors have from time to time qualitatively espoused the view that wave-like density variations observed in the atmospheric and lower ionospheric constituent layers are somehow due to layer response to gravity waves in the background atmosphere rather than due to some chemical or mechanical instability in the layer itself, the very large amplitudes observed in the density fluctuations of the layer structures remain a major obstacle to a quantitative resolution of such a view. Recently, the unifying feature of the gravity wave response mechanism was further strengthened by a consideration of Dudis and Reber (1976) who showed that density variations in the minor constituents of the neutral thermosphere obey relationships consistent with gravity wave perturbation of the background atmosphere, although the thermospheric collisional frequency may not be large enough to support the approximation that the constituents are strongly coupled to the wave motion by collisions (Del Genio et al., 1977).

In this paper we give a calculation of the linear and quasi-linear response of a constituent layer of general density profile to a gravity wave perturbation of the background atmosphere. It is assumed that the motion of the layer is collisionally coupled to the wave motion of the background neutral atmosphere; therefore, our results are applicable to layers below 200 km altitude only. Above 200 km altitude, the layer motion depends on gradient and diffusive drifts; however, since there are no interesting layer structures, except for the F-layer of the ionosphere, above 200 km, our assumption is quite adequate for the purpose of considering layer responses. We shall show that the amplitude of the density response of the layer is a strong function of

the gradient of the layer density profile relative to the scale height of the background neutral atmosphere. For sharply defined layers such as the ozone layer and the D and E regions of the ionosphere, the density response of the layer is of considerably larger amplitude than the wave density variation in the background neutral atmosphere. For cases where the layer response can no longer be regarded as a small perturbation, the exact quasi-linear solution shows singular behaviour at sufficiently sharp layer density gradients, thus signifying the onset of turbulence forced by gravity waves.

II. RESPONSE TO PERTURBATIONS.

Consider a constituent layer of density n(z) embedded in the neutral atmosphere of background density $N_0(z)$ which is stratified with scale height H_0. A linear gravity wave perturbation of density N, horizontal wind component V_x and vertical wind component V_z is assumed to exist in the background atmosphere. According to linear gravity wave theory, V_x and V_z are related to N/N_0 by

$$V_x = (ikg/\omega) (N/N_0) [\omega^2 \gamma H_0 - g (\gamma - 1)] / [i\omega^2 + g (\gamma - 1) K_z] \tag{1}$$

$$V_z = (N/N_0) [- g\omega (1 - i \gamma H_0 K_z)] / [i\omega^2 + g (\gamma - 1) K_z] \tag{2}$$

where g is the gravitational acceleration and $\gamma \equiv c_p/c_v$, the ratio of heat capacities. The wave density perturbation N/N_0 is given in terms of amplitude A and phase ϕ by

$$N/N_0 \equiv A \exp \phi \equiv A \exp (i\omega t - ikx - iK_z z) \tag{3}$$

where $K_z = k_z + i/2H_0$. Equation (3) defines the wave frequency ω, horizontal wave number k and vertical wave number k_z. The gravity wave perturbation forces a response in the constituent layer density n and the constituent velocity $\vec{v}$. For a neutral constituent layer, the constituent momentum equation relates the time rate of wave velocity variation to wave

gradient drifts and to collisional coupling to the background wave velocity $\vec{V}$. Since the neutral atmospheric collisional frequency below 200 km is orders of magnitude larger than the wave variations, the constituent momentum equation reduces to

$$\vec{v} = \vec{V} \ , \tag{4}$$

which is the usual assumption that the layer moves with the background medium. For an ionospheric layer in the E and F1 regions, the collisional coupling at frequency ν_{in} between ions and neutrals and the gyration about the magnetic field with frequency $\Omega_i = eB/m_i c$ are both much larger than the gravity wave frequency and drifts; therefore the constituent momentum equation is approximately

$$\Omega_i \vec{v} \times \hat{b} - \nu_{in} (\vec{v} - \vec{V}) = 0 \quad , \tag{5}$$

for low frequency gravity wave perturbations in the lower ionosphere. Inclusion of gradient drift terms in (4) and (5) can be easily accommodated; however, these terms will detract from the simplicity of our analysis without adding any significant content.

For constituent layers whose chemical and/or ionization equilibrium lifetimes are long compared to the gravity wave period, such as the ozone layer and the sporadic-E layer, the response of layer density n is governed by the continuity equation

$$\frac{\partial n}{\partial t} + \nabla \cdot (\vec{v}\, n) = 0 \quad , \tag{6}$$

where $\vec{v}$ is related to the gravity wave forcing velocity $\vec{V}$ by either (4) or (5). For ordinary ionospheric layers in the D and E regions at night, the recombination lifetimes are comparable to gravity wave periods; therefore, the effects of recombination must be taken into account in (6). The realization of the importance of recombination, when taken together with the results of the present analysis, is crucial in the consideration of nighttime E-region turbulence; however, for the sake of simplicity these effects will be dealt with elsewhere. Hence, our considerations here as applied to layers whose recombination lifetimes are shorter than or comparable to gravity wave periods will be regarded as indicative rather than quantitative results. For the remainder of the analysis, results based on (5) will be given without proof, since the derivation is entirely analogous to the one presented in terms of (4).

Without making a small perturbation assumption for layer response, the constituent layer density n can be written as the sum of a layer density profile in the absence of a gravity wave in the background atmosphere $n_0(z)$ and a gravity wave density response $\tilde{n}(x, z, t)$, i.e.

$$n = n_0(z) + \tilde{n}(x, z, t) \tag{7}$$

In our calculation, $n_0(z)$ is regarded as a general layer density profile generated by some production mechanism. Substitution of (4) and (7) into (6) yields the partial differential equation

$$\left(\frac{\partial}{\partial t} + \vec{V}\cdot\nabla\right)(\tilde{n}/n_0) + \left(\frac{1}{n_0}\frac{dn_0}{dz} - iK_z\right)(1+\tilde{n}/n_0)V_z - ik(1+\tilde{n}/n_0)V_x = 0\,, \tag{8}$$

which relates the layer density response $(\tilde{n}/n_0)$ to the background gravity wave perturbation (N/N_0) via (1) and (2). The layer density profile n_0 manifests itself in (8) in terms of a gradient length function $L(z)$, defined as

$$L(z) = \left[\frac{1}{n_0}\,\frac{dn_0}{dz}\right]^{-1}\,. \tag{9}$$

The boundary condition defined for (8) is that $(\tilde{n}/n_0)$ should vanish for vanishing gravity wave amplitude A in $(N/N_0) = Ae^{\phi}$. The general solution to (8) is very difficult to obtain not only because (8) depends on "second order" terms of the form $(\tilde{n}/n_0)(N/N_0)$ but also because L is an arbitrary function of z. Thus, the exact vertical structure of the response requires specification of a model of n_0. However, for purposes of interpretation it is much more advantageous to consider the local approximation for which $L(z)$ is a slowly varying function since the background wave is almost never a steady wave train. In this limit, it is a simple matter to solve the linear response version of (8). A more exact solution of (8) can be sought in the quasi-linear limit that the response $(\tilde{n}/n_0)$, similar to (N/N_0), depends on (x, z, t) through the phase function $\phi = i\omega t - ikx - iK_z z$. Inspection of (8) shows that indeed $(\tilde{n}/n_0)$ is purely a function of ϕ if the gradient length $L(z)$ is large compared to $(\partial\phi/\partial z)$, i.e. $k_z >> 1/L(z)$. Strictly speaking the quasi-linear limit is invalid at the layer peak where dn_0/dz vanishes; however, separate investigation in the neighborhood of the layer peak shows that the quasi-linear solution given below approaches the proper small perturbation response even when $L(z)$ approaches infinity, i.e. when dn_0/dz vanishes. In the quasi-linear limit, (8) can be transformed into a non-linear ordinary differential equation in ϕ, whose solution is given by

$$(\tilde{n}/n_0) = (\alpha/\delta)\,\ln\left[1 + (\delta/\beta)(N/N_0)\right] \tag{10}$$

where

$$\alpha = -\omega^2 + (g/H_0)(1 + H_0/L) - igK_z(1 + \gamma H_0/L)$$

$$\beta = -\omega^2 + ig(\gamma - 1)K_z$$

$$\delta = -(g/L)(1 - i\gamma H_0 K_z) + 2\omega^2 + 2ig(\gamma - 1)K_z$$

For low frequency gravity waves, i.e. $\omega^2 << g(\gamma - 1)/(\gamma H_0)$, $k_z >> 1/H_0$ and $\omega^2 k_z^2 \simeq k^2 g(\gamma - 1)/(\gamma H_0)$, we obtain

$$(\tilde{n}/n_0) \simeq -\frac{1}{\gamma - 1} \cdot \frac{[1 + \gamma H_0/L]}{[2 + \gamma H_0/(\gamma - 1)L]} \cdot \ln\left\{1 + (N/N_0)[2 + \gamma H_0/(\gamma - 1)L]\right\} \quad (11$$

In the small perturbation limit, (N/N_0) is infinitesimal and (11) approaches the limit

$$(\tilde{n}/n_0) \simeq -\frac{1}{\gamma - 1}(1 + \gamma H_0/L)(N/N_0) , \quad (12)$$

which is exactly the result obtained from (8) under the linear approximation. Further, for $L = -H_c$, the constituent scale height of a stratified atmospheric constituent, (12) is exactly the result of Dudis and Reber (1976).

For the ionospheric case (5), the situation becomes more complex since the orientation of the magnetic field is involved. If we consider equatorial E and F1 regions in the case for which the magnetic field is assumed to be perpendicular to the x - z plane, an analogous quasi-linear solution to (6) can

again be found, although the validity of quasi-linearity depends also on $k_z >> (d\,\Omega_i/dz)/\Omega_i$ and $k_z >> (d\,\nu_{in}/dz)/\nu_{in}$. The exact quasi-linear solution for this case is too complicated to be exhibited here; instead, the linear limit analogous to (12) will be given as a basis for interpretation in the next section.

$$(\tilde{n}_i/n_0) \simeq -\frac{1}{\gamma-1}\left\{1 + i\tilde{\nu}\gamma H_0 k_z + (\gamma H_0/L)[1 - \tilde{\nu}(1 + \Omega_i k/\nu_{in} k_z)]\right\}(N/N_0) \qquad (13)$$

where

$$\tilde{\nu} = (k_z/k)[\nu_{in}\Omega_i/(\nu_{in}^2 + \Omega_i^2)] \qquad . \qquad (14)$$

In the derivation of (13) and (14), the low frequency gravity wave approximation has been assumed. Note that in the D-region $\nu_{in} >> \Omega_i$ and $\tilde{\nu} << 1$, thus the response behaves exactly as that of a neutral layer. In the F-region $\nu_{in} << \Omega_i$ and (13) approaches the limit $(\tilde{n}_i/n_0) \approx -(N/N_0)/(\gamma-1)$, which does not depend on the layer structure.

III. INTERPRETATION

In this paper we shall limit our interpretation of the results of the previous section in terms of their application of layer structures in the atmosphere and lower ionosphere. The interpretation of the linear results for the particular case of density relations between stratified neutral thermospheric constituents of different masses has been undertaken by Dudis and Reber (1976).

For a general layer structure such as the ozone layer shown in Fig. 1, the inverse gradient length $1/L(z)$ is positive in the bottomside, vanishes at the layer peak and is negative in the topside. According to (12), which is more transparent for interpretation purposes then (10) or (11), one immediately obtains the result that the bottomside response is necessarily of larger amplitude than the topside response, whereas at the layer peak the response is given by $(\tilde{n}/n_0) \simeq -(N/N_0)/(\gamma - 1)$. Such a relationship is generally borne out in an examination of ozonesonde observations (Komhyr and Sticksel, 1967; Komhyr and Grass, 1968). The magnitude of response $(\tilde{n}/n_0)$ relative to the background wave (N/N_0) depends on the magnitude of the layer profile gradient $L(z)$ relative to the atmospheric scale height H_0. For a sharp layer density profile, $|\gamma H_0/L| > 1$, the layer density response $\tilde{n}/n_0$ can be considerbly larger than the background gravity wave density variation N/N_0. For example, on the bottomside of the ozone layer shown in Fig. 1 the "amplification" factor $|(1 + \gamma H_0/L)/(\gamma - 1)|$ is approximately 5, whereas on the topside this factor is approximately 2. Further, it is of interest to note that if $|\gamma H_0/L| > 1$ then the phase of the

response ($\tilde{n}/n_0$) is 180^o out of phase with (N/N_0) at the bottomside and near the layer peak, but the phase difference takes a 180^o jump just above the layer peak such that ($\tilde{n}/n_0$) becomes in phase with (N/N_0) at the topside. The apparent 180^o phase jump of ozone density variations just above the layer peak, shown in Fig. 1, may perhaps be interpreted in terms of this relationship. In the bottomside D and E regions of the ionosphere, very large wave-like density variations have been observed (e.g. Pfister and Ulwick, 1958; Knight, 1972). Again, these observations are qualitatively consistent with the relationship between the "amplification" factor of (12) or (13) and the variation of the layer density gradient L(z), although our results must be modified by inclusion of recombination effects.

The sporadic-E layer of metallic ions is of particular interest since the layer is sharply defined and the recombination lifetime is long compared to gravity wave periods. Recently, incoherent backscatter experiments have shown that the layer is strongly turbulent and exhibits large variations of density (Miller and Smith, 1975; 1976). Indeed, at times definite gravity wave effects can be identified (Miller and Smith, 1976). We wish to point out here that the "amplification" factor for the sporadic-E layer can be quite large. At the vicinity of 100 km altitude where sporadic-E occurs $\nu_{in}/\Omega_i \sim 30$; therefore the ionospheric layer relation (13) collapses to that of the neutral layer relations (11) and (12). Since L for the sporadic-E layer is of order of 1 km and H_0 is of order of 8 km, $\gamma H_0/L$ is sufficiently large that the linear relation (12) becomes invalid and our interpretation must rely on the quasi-linear relation (11). For a background gravity wave with $| N/N_0 | \sim 10\%$,

we obtain the sporadic-E layer response amplitude $|\tilde{n}/n_0| \sim 1.4$, which certainly signifies the formation of very dense knots of sporadic-E layer density observed by Miller and Smith (1976). Indeed, for gravity waves with $k_z \sim 1/L(z)$, even the quasi-linear solution becomes invalid and the response $(\tilde{n}/n_0)$ is dominated by a resonance between the layer structure and the wave structure which would result in turbulence. Although the exact non-linear solution for such a case is too difficult to obtain, that the layer response presages turbulence in such a case can be argued from a consideration of the relative phase between $(\tilde{n}/n_0)$ and (N/N_0) in (11). When $|\gamma H_0/L| >> 1$ in (11), the complex argument of the logarithm in (11) may approach its negative real axis branch cut; as a result, the phase of $(\tilde{n}/n_0)$ may take on an infinite number of branch values separated by multiples of π. The major characterization of turbulence is that the phases of its density variations are not well correlated. Based on these considerations, we would like to suggest that gravity wave forcing is the major mechanism in the generation of density irregularities in sharply defined constituent layers of the atmosphere and ionosphere. Further, sharp layer gradients are necessarily "turbulent".

The generation of turbulence is of great interest in the nighttime equatorial ionosphere in the 200 km region. It has been suggested that the nighttime equatorial F-region is susceptible to Rayleigh-Taylor instability (e.g. Woodman and LaHoz, 1976; Hudson and Kennel, 1975); however, the Rayleigh-Taylor growth rate in the 200 km region, $g/(2\nu_{in}L) \approx 10^{-4}$ sec^{-1}, is sufficiently small that gravity wave response effects at wave

period short compared to Rayleigh-Taylor growth time may be more important. We wish to point out here that the gravity wave response at the bottomside of the layer is subject to Rayleigh-Taylor instability also. An analysis of the gravity wave response of an ionospheric layer structure in the limit $\nu_{in} << \Omega_i$ shows that internal wave modes are also susceptible to Rayleigh-Taylor growth. Since internal wave modes, unlike the surface waves of the pure Rayleigh-Taylor instability, can propagate throughout the layer structure, we would expect that gravity wave response at the steepened bottomside of the nighttime equatorial ionospheric layer structure will play a major role in the "bottomside turbulence" phenomenon. Detailed analysis of such a situation will be given elsewhere.

As a final example, we wish to consider the atomic oxygen layer which maximizes slightly above the mesopause at altitudes between 90 and 100 km. Although very few direct measurements of the atomic oxygen distribution in this region of the atmosphere are available, some examples of wave structure may be seen in the rocket-borne mass spectrometer data presented by Philbrick et al. (1973, 1974). In these cases the wave amplitudes were relatively modest (~10 - 15%) and no wave features were apparent in the simultaneously measured background gas profile. This behavior is consistent with our theory since the amplification factor is predicted by (12) to be about 2.5 at the layer peak and larger below the peak. Further evidence of irregular structure in the atomic oxygen distribution near the layer peak, which would appear as wave-like oscillations in a vertical profile, may be found in latitude-altitude contours derived by Wasser and Donahue (1978) from 5577-Å airglow measurements. In these remotely-sensed data under-dense "patches" are seen particularly, though not exclusively, on the bottomside of the layer. The latitudinal extent of the patches is a few degrees, i.e. of the order of a few hundred kilometers. It would be interesting to determine in the future whether wave perturbations of the stratospheric ozone layer may similarly be "patchy" in their horizontal extent.

IV. CONCLUSION

By comparing observations with the solution of the linear and quasi-linear problems of the density reponse of a neutral or ionospheric layer structure of gravity wave perturbations in the background atmosphere below 200 km altitude, we conclude that large wave-like and turbulent density variations in the ozone layer and the sporadic-E can be interpreted as layer density response to gravity waves. Limited observations of wave structure in the atomic oxygen profile near its maximum also support this interpretation. The layer density response is generally of larger amplitude at the bottomside than at the topside, although the amplitude of both depends on the relative sharpness of layer density gradient in comparison to the gradient of background atmosphere stratification. It is suggested that gravity wave response plays a major role in the generation of turbulence in the nighttime equatorial ionosphere at the 200 km region.

REFERENCES

Del Genio, A. D., J. M. Straus, and G. Schubert, Effects of Wave-Induced Diffusion on Thermospheric Acoustic-Gravity Waves, Submitted to Geophys. Res. Letters 1977.

Dudis, J. J., and C. A. Reber, Composition Effects in Thermospheric Gravity Waves, Geophys. Res. Letters, 3, 727, 1976.

Faire, A. C., E. A. Murphy, and R. O. Olson, Atmospheric Density, Temperature and Winds Measured During Aladdin II, Space Research XIV, p. 97, Akademie-Verlag, Berlin, 1974.

Fogle, G., and B. Haurwitz, Noctilucent Clouds, Space Sci. Rev., 6, 279, 1966.

Hines, C. O., Internal Atmospheric Gravity Waves at Ionospheric Heights, Can. J. Phys., 38, 1441, 1960.

Hudson, M. K., C. F. Kennel, Linear Theory of Equatorial Spread-F, J. Geophys. Res., 80, 4581, 1975.

Knight, P., A Classification of Night-Time Electron Density Profiles, J. Atm. Terr. Phys., 34, 401, 1972.

Komhyr, W. D., and R. D. Grass, Ozonesonde Observations 1962-1966, ESSA Technical Report ERL 80-APCL3, Vol. II, 1968.

Komhyr, W. D., and P. R. Sticksel, Ozonesonde Observations 1962-1966, ESSA Technical Report IER 51-IAS 1, Vol. I, 1967.

Miller, K. L., and L. G. Smith, Horizontal Structure of Midlatitude Sporadic-E Layers Observed by Incoherent Scatter Radar, Radio Science, 10, 271, 1975.

Miller, K. L., and L. G. Smith, Midlatitude Sporadic-E Layer, Thesis by K. L. Miller, Aeronomy Laboratory, University of Illinois, Urbana, Ill., Library of Congress ISSN0568-0581, 1976.

Pfister, W., and J. C. Ulwick, The Analysis of Rocket Experiments in Terms of Electron Density Distributions, J. Geophys. Res., 63, 315, 1958.

Philbrick, C. R., G. A. Faucher, and E. Trazcinski, Rocket Measurements of Mesospheric and Lower Thermospheric Composition, Space Research XIII, p. 255, Akademie-Verlag, Berlin, 1973.

Philbrick, C. R., D. Golomb, S. P. Zimmerman, T. J. Keneshea, M. A. MacLeod, R. E. Good, B. S. Dandkar, and B. W. Reinisch, The Aladdin II Experiment: Part II, Composition, Space Research XIV, p. 89, Akademie-Verlag, Berlin, 1974.

Wasser, B., and T. M. Donahue, Atomic Oxygen Between 80 and 120 km: Evidence for a Rapid Spatial Variation in Vertical Transport near the Mesopause, to be published in J. Geophys. Res., 1978.

Webb, W. L., Structure of the Stratosphere and Mesosphere, p. 146, Academic Press, New York, 1966.

Woodman, R. F., and C. LaHoz, Radar Observations of F Region Equatorial Irregularities, J. Geophys. Res., 81, 5447, 1976.

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El Segundo, California

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